LABORATORY COURSE IN PHYSIOLOGICAL PSYCHOLOGY.

By Edmund C. Sanford, Ph. D.

(*Fourth Paper.*)

V.—VISION. (*Continued.*)

Seeing of Light and Color.

The aim of the following experiments is not to adjudicate conflicting color theories, but rather to present the most important experimental facts that all color theories must regard.[1] Authoritative accounts of the theories may be found as follows: Young-Helmholtz theory; Helmholtz, Handbuch der physiologischen Optik,[2] 2te Aufl., pp. 344-350. G[1] 290-294, 320-321, 367; F. 380-387, 424-425, 484. Also Popular Scientific Lectures, 1st Series, New York, 1885, pp. 249-256. Hering's theory; Hering, Zur Lehre vom Lichtsinne, pp. 70-141, (two communications to the Vienna Academy, April 23 and May 15, 1874); Ueber Newton's Gesetz der Farbenmischung, pp. 76-79, a very brief account of his own in connection with a general account of theories. These are the most prominent theories, and something on them, especially on the first, will be found in the physiologies and in some works on the use of color in the arts. Other theories more or less different from these will be found as follows: V. Kries: Die Gesichtsempfindungen und ihre Analyse, Du Bois-Reymond's Archiv, 1882, Supplement-Band, vi, 1-178. Wundt: Physiol. Psychol., 2te Aufl., pp. 453-456; 3te Aufl., 491-496. Also Philos. Studien, IV, 1888, 355-389. Donders: Ueber Farbensysteme, Archiv für Ophthalmologie, XXVII, 1881, H. 1. Noch einmal die Farbensystem, *ibid.*, XXX, 1884, 1. Göller: Die Analyse der Lichtwellen durch das Auge. Du Bois-Reymond's Archiv, 1888. Christine Ladd Franklin, Eine neue Theorie der Lichtempfindungen. Zeit. für Psychol., IV, 1892, 212.

On color vision in general may be mentioned, besides these works of Helmholtz, Hering and Wundt: Fick: Qualität der Lichtempfindungen, Hermann's Handbuch der Physiologie, III, Th. i, pp. 160-232. Maxwell: On the Theory of Compound Colours

[1]For concise statements of these facts, see Wundt, Physiologische Psychologie, I, 487 (cited by Ladd, Phys. Psych., 338), also p. 501, and Christine Ladd Franklin, Zeit. für Psych., IV, 1892, 212.

[2]The second edition of Helmholtz's great work is as yet incomplete. The latest complete edition is the French translation, Optique physiologique, Paris, 1867. To facilitate reference when pages are cited, the numbers are given preceded by G[2] for the second German edition, and by G[1] for the first German edition, and by F. for the French translation. Occasional errors in the pages for G[1] may have crept in, for that edition was not at hand and the pages for it have been taken from the double paging in G[2] and F. The error can hardly amount, however, to more than a page one way or the other.

and the Relation of the Colours of the Spectrum, Phil. Trans. 1860; and On Colour Vision, Proc. Royal Institution of Great Britain, VI; reprinted in Maxwell's Scientific Papers, I, 410-440; II, 267-280. Rood: Students' Text-book of Color, New York, 1881. Aubert: Physiologie der Netzhaut, Breslau, 1865; also Grundzüge der physiologischen Optik, Leipzig, 1876, pp. 479-572. This work forms part of the second volume of Graefe und Saemisch's Handbuch der gesammten Augenheilkunde. Charpentier: La Lumière et les Couleurs, Paris, 1888. Von Bezold: The Theory of Color in its Relation to Art and Art Industry, Boston, 1876. Benson: Manual of the Science of Colour, London, 1871, pp. xii, 58. Chevreul: The Principles of Harmony and Contrast of Colors, London, 1859. Le Conte: Sight, New York, 1881. Ladd: Elements of Physiological Psychology, New York, 1887. Beaunis: Nouveaux Éléments de Physiologie Humaine, Paris, 1888; and other standard physiologies.

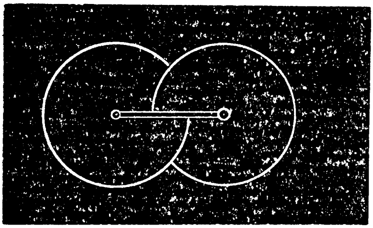
Apparatus. In addition to the blue and red glass, the colored papers and the black and white cardboard used in the previous section, there will be required for this, pieces of yellow, green and violet glass, or of colored gelatine (see below), a small pane of clear glass, a mirror, a sheet of white tissue paper or other semi-transparent paper, and pieces of gray paper or cardboard of different intensities. Gray papers can be made by painting white paper over with India ink; or a tolerable substitute may be made by overlaying black paper or cardboard with one or more thicknesses of tissue paper.

For some of the contrast experiments (Ex. 141 ff.) the gummed parquetry rings and the lentil dots used by the kindergarteners are extremely convenient, and are not expensive. The rings are 1, 1 1-2 and 2 in. in diameter and 1-8 in. broad and are to be had in a considerable variety of colors; the dots are 1-4 in. in diameter, and in six colors. See catalogue of the Milton Bradley Co., Springfield, Mass., pp. 49 and 71.

The standard of color when exactness is important is, of course, the spectrum; and experiments with pure (*i.e.*, monochromatic) spectral colors are the final appeal. The apparatus required for a complete study of color sensations with spectral colors, especially when quantitative results are aimed at, is extremely refined and correspondingly expensive. The spectrophotometer pictured on p. 355 of Helmholtz's Physiologische Optik, 2te Aufl., is quoted by the makers, Franz Schmidt und Haensch, Stallschreiber-Strasse 4, Berlin, S., at mk. 750. Other apparatus of similar purpose ranges from mk. 375 to mk. 3500. The spectrophotometer of the Cambridge Scientific Instrument Co. costs £15. Simple qualitative experiments like those of this section can, however, be made without very expensive apparatus, and for the most part without spectral colors. Where spectral colors are employed a simple prism (costing from 15 cents upward), or at most an ordinary spectroscope, such as is found in every chemical and physical laboratory, will serve amply. A pocket spectroscope even, costing from $5 or $6 upward, will show a good deal, and is useful in determining approximately the composition of light transmitted by colored glass. If nothing more is done, it is desirable that the experimenters familiarize themselves with the appearance of the spectral colors and the chief Fraunhofer lines as landmarks in the spectrum. By combinations of thin sheets of colored gelatine, light that is practically monochromatic can be secured; see a paper by Kirschmann, Ueber die Herstellung monochromatischen Lichtes, Wundt's Philos. Studien, VI, 1891, pp. 543-551. Such sheets are used before calcium lights in the

theatre for the projection of colored lights upon the stage, and may be had of dealers in stereopticons. A. T. Thompson & Co., 13 Tremont Row, Boston, sell red, yellow, green, blue, violet and purple in sheets, 20 1-2x16 3-4 inches, at 25 cents a sheet. For many purposes these sheets are as good or better than colored glass.

For the study of the phenomena of color-mixing with artificial colors, the most satisfactory instrument is the color top or rotation color-mixer in some one or other of its numerous forms. One of these was mentioned in the introduction to the previous section on the Mechanism of the Eye and Vision in General, namely, a little electric motor. All the experiments of this section that require a color-mixer can be made with such a one. Many if not all of them could be made with the color tops sold as toys, or with the very simple one suggested by Dr. Bowditch in his Hints on Teaching Physiology, to wit, a button-mold fitted with a peg and spun with the fingers. One made of a button-mold an inch and three quarters in diameter and carrying disks two and a half inches in diameter, shows the contrast effects of Ex. 142*d* as elegantly as could be desired. The disks are held in place by a piece of rubber tubing of very small bore fitting snugly upon the stem and twisted down upon the disk like a nut. Larger apparatus specially designed for color-mixing may be had of all physical instrument dealers. Among the rest may be mentioned the *Farbenkreisel* made by R. Rothe, Mechaniker des physiologischen Instituts der k. k. Universität, Prag (Wenzelsbad), at mk. 30. A fine instrument by the same maker for rotating a horizontal disk either by foot or hand, with additional parts for studying the color-blindness of the peripheral parts of the eye, costs mk. 160. The color-mixer of the Milton Bradley Co., Springfield, Mass., costs $10, including disks, etc.; the color-mixers of the Cambridge Scientific Instrument Co., St. Tibb's Row, Cambridge, England, cost £6-10 and £10. R. Jung, Heidelberg, has rotation apparatus, including one that moves by clock-work at mk. 50-65 with disks. The important thing in such a piece of apparatus is that it should rotate rapidly enough to give a smooth and steady mixture of two colors when these occur but once each upon the disk, *e. g.*, to give an even gray with a disk that has a solid 180° of black and a solid 180° of white. When this is the case the two disks may be slipped together, as in the cut, and any required proportion of the colors easily arranged.



If the rotation is not sufficiently rapid the sectors must be made smaller and more numerous, *e. g.*, four sectors of black of 45° each separated by four sectors of white of the same size. This is not difficult when the proportions of color are to remain constant, but where adjustments are to be made the multiplicity of sectors is a disadvantage. Rothe and the Milton Bradley Co. supply colored paper disks in considerable variety evenly cut, and this is an important point, for if the cutting is inexact the disks will appear with bothersome fringes of color when in rotation. The centre hole in Rothe's disks is of course cut to fit the Rothe color mixers. His disks may be had in two sizes, 20 cm. and 11 cm. in diameter, at prices ranging from 60 to 105 kr. per doz. for the large, and 20 to 30 kr. for the small, according to color. Colored papers of excellent color and surface (shiny papers are to be avoided) may be had of R. Jung, Heidelberg.

A rotation apparatus that will serve excellently for class demonstrations is a carpenter's polishing lathe, which is to be obtained at some hardware stores and sells at $4.50. It can be screwed to the table and worked by the hand or foot. Unfortunately it can hardly be made to rotate rapidly enough to blend 180° of white with 180° of black, but for fixed disks with more numerous sectors it works excellently; and though made for so remote a purpose can be used without change and will carry disks up to a foot in diameter. With a very little alteration it would carry them twice as large. Perhaps a maximum of simplicity is reached in the use of a boys' "buzzer" as a color-mixer, which the writer has heard recommended, but never tried. Special disks for use in certain experiments are shown in cuts accompanying them.

In addition to the color-mixer and disks, a stereoscope and stereoscopic diagrams (see cuts accompanying the experiments) and a double refracting prism will be needed. Any stereoscope will answer, but the hood and the central partition should be removed. The double refracting prism may be purchased at no very great expense from dealers in physical instruments.

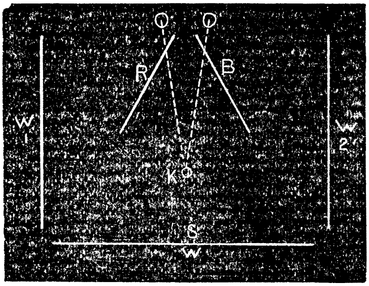
In Ex. 142*b* and 148*b*, a small wooden frame made by fixing two pieces of board 6x6 in. together at right angles, is needed (see diagram accompanying Ex. 142*b*). The convenience of the instrument is much increased if guide strips of wood or metal are attached to the vertical and horizontal pieces, so that the diagrams to be used upon them will be held in place and yet be easily interchangeable. For exhibiting a very deep black in Ex. 130*a*, a black box may be prepared as follows. Make a light tight wooden box 8x10x12 inches in size; cut a two-inch hole in one end and have the whole painted a dull black, both within and without. Before closing it finally, divide it by a slanting partition running obliquely upward and forward from the back edge of the bottom to a point on the top about four inches from the front. The front side of this partition should be covered with black velvet. In comparison with the black that is seen on looking through the hole against this slanting velvet, the gray character of the black paint, of ordinary black cardboard, and even of black velvet, is easily recognized.

The easiest test for color-blindness is made with colored worsteds, which may be had of any dealer in oculists' supplies. An approved selection of colors in sufficient variety is sold by N. D. Whitney & Co., 129 Tremont street, Boston, Mass., at $2.50. A small card of wools for testing color vision is to be found on the inside cover of Galton's Life History Album, London, Macmillan & Co., 1884.

Apparatus is helpful in measuring out the color fields in Ex. 128, though it need not be elaborate. At its simplest two things are necessary: something for steadying the head, and a broad surface perpendicular to the line of sight on which to map out the color fields. A block on which to rest the chin and a convenient wall might do. If something a little more permanent is desired, the head-rest shown in the last section (*American Journal of Psychology*, IV. 1891-92, 474) can be clamped to the front edge of a narrow table, and a screen of light boards (or better, a wooden frame covered with black or gray cloth) fastened about a foot back from it. This distance must not be great, or the screen will need to be of excessive size. It is well to paste a vertical and horizontal scale upon the screen crossing at the point immediately before the eye, so that distances may at once be read off. Such an instrument is known as a *campimeter*. A more perfect instrument for this purpose is the *perimeter*. Of this instrument there are many forms; that of Priestly Smith is perhaps as convenient as any except the most elaborate

ones. In this instrument, not to attempt a detailed description, the place of the screen is supplied by a curved arm that can be turned about an axis at the point on which the eye is fixed, and in turning would describe a hemisphere of which the eye is the centre and the fixation point the pole. The arm is marked for every 5°, and the limits of the field of vision on any meridian can at once be read off and recorded. The record is made by a needle prick in a diagram carried by the instrument, a new diagram being inserted for each eye tested. The price of this instrument from R. Jung, Heidelberg, is mk. 60, from New York dealers $30.

For Ex. 145 and 151 an apparatus devised by Hering and described by him in the *Zeitschrift für Psychologie*, I, 1890, 23-28, is extremely convenient. It is made by R. Rothe of Prag at 28 marks. The apparatus is simple, however, and any carpenter can make of wood one that will answer. The first aim of this instrument is to secure a binocular mixture of blue and red. For that purpose blue and red glasses before the eyes may be used, provided that a good deal of white can also be mixed in with the color of the glass. This is done by letting the glasses stand at an angle before the eyes and reflect on their upper surface the images of suitably placed white screens. The quantity of white light is regulated by the position of the screens with reference to the source of illumination and by the inclination of the colored glasses. The following cut shows diagrammatically what the arrangement of glasses and screens is.



In the cut W_1 and W_2 are the screens just spoken of, *R* and *B* the red and blue glasses, *W* a white surface carrying a narrow black strip at *s*, and *k* is the point upon which the eyes are fixed. In an instrument made by a carpenter for the laboratory of Clark University, the following plan was followed; it is here reproduced not because it is the best, but for the sake of definiteness. The stuff used in the instrument was almost all seven-eighths of an inch thick, and that thickness may be understood except where something else is stated. The base is a board 30 in. long, 12 in. wide. In the middle of this is placed another board 12 in. long and 10 in. wide, leaving a margin of an inch on each side and of nine inches at the ends. This little platform bears the white cardboard corresponding to *W* in the diagram. On the nearer edge of this platform is fastened an upright post 15 in. high, 3 in. wide. At its upper end on the forward side this post carries the frames that hold the glasses *R* and *B*. The glasses are 4 in. square, and are framed on three sides only, the upper edge being left free so that the glasses may come close to the eyes. The frames are small pieces of board 6 in. long, 5 in. wide with a square piece (three and three-quarters inches on the side) taken from the middle of their upper ends, leaving them like a U with very square corners and a heavy bottom. Over these square holes the glasses are fastened. The frames are fastened with a single screw each to the post, the screws penetrating the frames about an inch and a half from the free edge of the glass. When in position, the glasses rise about three-quarters of an inch above the top of the post, and stand like the sides of a roof. They do not quite meet, however, but leave a space for the observer's nose between them when the apparatus is in use. The screws that hold

the frames should be tight enough to hold the frames in position, but not so tight as to prevent their turning in adjustment. On the front of the post and about six inches upward from its foot is a wire about three and a half inches long, extending forward from the surface of the post and perpendicular to it. At its end is a little button of cork, the fixation point *k* in the diagram. The side screens of the instrument are exactly alike and the description of one will do for both. Each screen is a piece of half-inch board 9 in. wide and 13½ in. long. This board turns midway from top to bottom on a horizontal axis and in a light frame just large enough to enclose it. The frame itself is fastened to a broad piece of board which forms its base and rests in turn on the base board of the instrument. A peg in the middle of the first of these, fitting into a hole in the last, allows the rotation of the frame and screen about a vertical axis. The screen is thus made adjustable in any direction. Its face is covered with white cardboard. The only remaining part of the instrument is the strip of black paper, a quarter of an inch wide, represented by *s* in the diagram, which is pasted on *W* perpendicular to the post. It is highly important that *W* be without speck or spot, and that the colored glasses be as free from flaws as possible. The instrument as described is intended for binocular contrast. For binocular color-mixing, other pieces of glass besides red and blue are needed for other combinations and the black strip is not required.

Another simple demonstrational instrument of Hering's contriving is for the study of changes of brightness in colors and can also be adapted for contrast. Its principle is the same as that used in the side screens in the last instrument, namely, change of position with reference to the source of illumination. A white card, provided that its surface is not shiny, receives a maximum of light and looks brightest when it stands perpendicular to the light. As it is turned and the light falls obliquely upon it, it receives less and less and looks darker and darker. If it is shiny, as most paper and cardboard are, this change is not uniform, but this does not much interfere in this instance. The paper used should, however, be dull finished. The instrument at its simplest is a tall box open in front and with a hole in the top to look through. It is painted black inside and contains a screen that can be turned about a horizontal axis, and thus receive light perpendicularly or obliquely as desired. It is, however, convenient to have a frame instead of a permanent screen so that a number of cards of different color or brightness can be interchanged, and to have the box double so that two frames can be used side by side and comparative tests can be made. When contrast is to be introduced, a second pair of frames above the first and high enough so as not to shade them are introduced. The cards that are used in these upper frames must each be pierced with a hole, say 2x4 cm., near the middle, in such a position that when the eye looks through them from the top of the box, nothing but the card in the frame below can be seen. The hole must be carefully and cleanly cut, and the edge, if it shows white, must be colored like the surface of the card. When such a hole is looked at with a single eye, it is easy to conceive the part of the lower card seen, not to be really below, but a part of the upper card itself. This illusion might be strengthened by the use of a feebly convex lens to exclude exact accommodation. Changes of the inclination of the upper frame (provided there is no reflection from its under surfaces) can produce no real change in the illumination of the lower one, but very striking changes seem to follow such changes of the upper one. This instrument in finished form, though without the additional

frames for contrast, can be had like Hering's other apparatus of his mechanic, R. Rothe, Prag.

Many of the color experiments to follow can be demonstrated before a considerable audience by the use of a projection lantern, and some makers of lanterns have diagrams for contrast colors, etc. Their preparation, however, can offer little difficulty to those familiar with the use of the lantern and with the ordinary forms of the experiments.

A given color sensation may be changed in three ways: in *color-tone*, in *intensity*, and in *saturation*, or to use Maxwell's terms, in *hue*, *shade* and *tint*. Changes in *color-tone* are such as are experienced when the eye runs through the successive colors of the spectrum. Changes in *intensity* are changes in the brightness of the color. Changes in *saturation* are such as are produced by the addition of white; when much white light is added, the color is a little saturated. Changes in intensity and saturation if excessive involve some change of color-tone also. The number of primary colors is various in various theories; red, green and violet (or blue) are selected by the supporters of the Young-Helmholtz theory, red, green, yellow and blue by Hering, Mach and others, while Wundt is indisposed to make any particular ones more original for sensation than the rest.

127. Color-blindness. Holmgren's method. Spread the worsteds on a white cloth in good daylight. Pick out a light green (*i. e.*, a little saturated green) that leans neither toward the blue nor the yellow; lay it by itself and require the person to be tested to pick out and lay beside it all other skeins that are colored like it, not confining himself, however, to exact matches, but taking somewhat darker and lighter shades also, so long as the difference is only in brightness and not in color-tone. Do not tell him to pick out "the greens" nor require him to use or understand color words in any way; simply require the sorting. If he makes errors, putting grays, light browns, salmons or straws[1] with the green, he is color-blind; if he hesitates over the erroneous colors and has considerable difficulty, his color-vision is probably defective, but in a less degree. If the experimentee makes errors, try him further to discover whether he is red-blind or green-blind by asking him to select the colors, including darker and lighter shades, that resemble a purple (near magenta) skein. If he is red-blind, he will err by selecting blues or violets, or both; if he is green-blind, he will select green or gray, or both, or if he chooses any blues and violets, they will be the brightest shades. If he makes no errors in this case after having made them in the previous case, his color-blindness is incomplete. Violet blindness is rare. Complete certainty in the use of even such a simple method as this is not to be expected without a full study of the method and experience in its application.

On color-blindness and methods of testing for it cf. Helmholtz: Op. cit. G[2] 357 372, 456-462; G[1] 294-300, 847-848; F. 388-400. Jeffries: Color-blindness, its dangers and its detection, Boston, 1879 (this work contains a seventeen-page bibliography on color-blindness and kindred topics); also an article on Color-blindness in the Reference Handbook of the Medical Sciences, New York, 1886, II, 241. Rayleigh and others: Report of the Royal Society's Committee on Colour Vision. Proc. Royal Soc., LI, No. 311, July 19, 1892. Hering: Zur Diagnostik des Farbenblindheit, Archiv für Ophthalmologie, XXXVI, 1890, Heft i, 217-233; also Die Untersuchung einseitiger Störungen des Farbensinnes mittels binocularer Farbengleichungen. Arch. f. Ophthal., XXXVI, 1890, H. 3, 1-23. See also a

[1] It is difficult to give the tints accurately in words. The experimenter should consult the colored charts given in the books of Jeffries mentioned in the bibliography.

paper by Hess in the same place, pp. 24-30. Kirschmann: Beiträge zur Kenntniss der Farbenblindheit, Wundt's Philos. Studien, VIII, 1892, Hefte 2 u. 3. Helmholtz, Hering, Kirschmann and others give exact methods for determining the particular colors that are lacking. On differences in the apparent extent of the spectrum in different observers, see Morgan: Animal Life and Intelligence, pp. 280-283.

128. Vision with the peripheral portions of the retina. *a*. Campimetry. Color-blindness is normal on the peripheral portion of the retina. At the very centre the pigment of the yellow spot itself interferes somewhat with the correct perception of mixed colors containing blue (cf. Ex. 110). In a zone immediately surrounding this all colors can be recognized. Outside of this again is a second zone in which blue and yellow alone can be distinguished, and at the outermost parts not even these, all colors appearing black, white or gray. The zones are of course not sharply bounded, but blend into one another, their limits depending on the intensity and area of the colors used. *a*. With the campimetrical apparatus at hand, find at what angles from the centre of vision on the vertical and horizontal meridians of the eye the four principal colors, red, yellow, green and blue, can be recognized; try also for white. Keep the eye steadily fixed on the fixation mark of the instrument and have an assistant slide the color (say a bit of colored paper 5 mm. square pasted near the end of a strip of black cardboard an inch wide) slowly into the field from the outside. It will be well to move the paper slowly to and fro at right angles to the meridian on which the test is made, so as to avoid retinal fatigue. Take a record of the point at which the color can first be given with certainty. Repeat several times and average the results. The size of the colored spot shown should be constant for the different colors, and the background (preferably black) against which the colors are seen should remain the same in all the experiments. *b*. Repeat the tests with a colored square 10 mm. on a side, and notice the earlier recognition of its color as it approaches from the periphery. *c*. Try bringing slowly into the field (best from the nasal side) bits of paper of various color, especially violet, purple, orange, greenish yellow and greenish blue; or better, hold the bit of paper somewhat on the nasal side of the field and turn the eye slowly toward it, beginning at a considerable angle from it. If the paper is held before a background, containing a line along which the eye can approach the paper, the eye will be assisted in making its approach gradual. Observe that on the outer parts of the retina these colors first get their yellow or blue constituents, and only later the red or green, and appear in their true color. If the range of choice is sufficiently large, it may be possible to find a red (inclined toward red purple), a green (inclined toward the blue), which, like pure blue and yellow, change only in saturation and not at all in color tone as they move inward toward the centre of the field. These four colors are the *Urfarben* or primary colors of Hering.

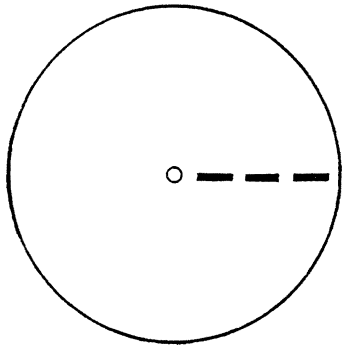
Helmholtz: *Op. cit.*, G2 372-374, F. 399-400. Hess: Ueber den Farbensinn bei indirektem Sehen, Archiv für Ophthalmologie, XXXV, 1889, H. 4. Hering: Ueber die Hypothesen zur Erklärung der peripheren Farbenblindheit, Arch. f. Ophth., XXXV, 1889, H. 4, pp. 63-83; XXXVI, H. 1, 264. Fick: Zur Theorie des Farbensinnes bei indirektem Sehen, Pflüger's Archiv, XLVII, 1890, 274-285. Aubert, Phys. Opt., 539-546.

129. Changes in color tone. With spectral lights, change of vibration rate, if not too small, means change of color tone, but equal changes in vibration rate do not involve equal changes in color tone. The change of color tone is most rapid in the green region of the spectrum, less rapid at the red and violet ends. *a*. With the spectroscope and daylight find the characteristic *D*, *E*, *F* and *H* lines. The *D* line lies in the golden yellow, *E* in the green, *F* in the blue, and *H* at the end of the violet. Between the *D* line and

the F line, the vibration rate changes from 526 to 640 billion vibrations per second, and the color runs from yellow, through green to blue, while from F to H, with the greater change in vibration rate from 640 to 790 billion per second, the change is only from blue to violet. *c.* Notice the tendency of the succession of spectral colors to return upon itself, shown in the resemblance of the red and violet.

Helmholtz: *Op. cit.*, G² 289, 320, G¹ 237, F. 319. Rood: *Op. cit.*, 27. Wundt: *Op. cit.*, I, 429. Fick: *Op. cit.*, 173-175, 183. Aubert, Phys. Opt., 530.

130. Changes in intensity. Black and white. Black and white are the extremes of intensity in the series of grays. The ordinary black and white of conversation are considerably short of these extremes. *a.* Compare a bit of black velvet or black cardboard with the black of the black box described above. *b.* Compare ordinary white paper in diffused light with the same in direct sunlight or with a brightly illuminated white cloud. *c.* Just observable differences with medium intensities. Prepare a disk like that shown in the accompanying cut by drawing along a radius of the disk a succession of short lines of equal breadth. Let the breadth of the line correspond to about one degree on the edge of the disk. Since the breadth of the line is everywhere the same, it will occupy a relatively greater portion as it nears the centre. When the disk is set in rapid rotation, each short line will give a faint gray ring, those at the outer edge being very faint, those nearer the centre, darker. Find which is the faintest ring that can be seen, and calculate the proportions of black and white in it.[1] The ratio of the black to the white measures approximately the just observable decrease in intensity below the general brightness of the disk. The results of Helmholtz and Aubert are respectively: Helmholtz, 1:117 to 1:167. Aubert, 1:102 to 1:186, the differences depending on the intensity of the general illumination of the disk. Some wandering of the eyes is helpful, but too rapid motions of the eyes, which tend to break up the even gray of the rings, must be avoided. It is absolutely essential to have the rotation very rapid and perfectly free from vibration — so rapid that with the moderate motions of the eyes, the uniform gray of the rings is not disturbed. If great rapidity is impossible, replace the single black line by two of proportionately less breadth on opposite sides of the disk, or by four at 90°.



Helmholtz: *Op. cit.*, G², 384 393, G¹, 310-316, F. 411-419. Aubert: Physiol. Optik., 489-492.

131. Changes in intensity. Colors other than black and white. At their maximum intensity, all colors tend toward white or yellowish white, green becoming first yellow and then white, red progressing hardly beyond the yellow, but blue and violet easily reaching white.

[1] The formula for the amount of black, assuming that the radial line is absolutely black, and taking some arbitrary point of the line, *e. g.*, the middle point, for the calculation, is of course $\frac{b}{2\pi r}$, where b is the breadth of the radial line and r the distance of the chosen point from the centre of the disk.

a. Fix a prism in the sunlight so that it projects an extended spectrum on the wall. Hold a card, pierced with a pin-hole, before the eye, and bring the eye successively into the different colors, looking meanwhile through the pin-hole at the prism. Something of the same kind may be seen by looking through pieces of colored glass at the disk of the sun behind a cloud (in which case the portions of the cloud seen at the sides of the glass afford a means of comparison), or at the image of the sun reflected from an unsilvered glass plate, or by concentrating light from colored glass on white paper with a convex lens. *b*. It is easy to reduce the intensity of colors with the color-mixer by spreading the light of a colored sector over the whole surface of a disk otherwise black.[1] Make a succession of mixtures of red and black on the color-mixer, beginning with a proportion of red that makes a barely observable change, and increase the proportion till the red decidedly predominates in the mixture. Place a smaller disk of black over the larger disks so as to have a standard black in the field. If any of the red shows through either black disk several of the latter should be used together to prevent it. Try also with the other chief colors. Disks like the diagram (in which shaded parts stand for color and solid black for black) show the whole series of such gradations at once, though not quite so satisfactorily. *c*. Carry a number of small slips of colored paper into a darkened room, or look at them through a fine needle hole in a card, and notice the order in which they lose their color quality. *d*. Adjust the spectroscope so that the chief Fraunhofer lines can be seen, and then gradually narrow the slit through which the light enters the instrument. Observe that red, green and violet-blue with a trace of yellow persist longer than the intermediate colors, and that when all the color is gone, there still remains some light in the region of the green. This experiment must be performed in a dark room, or the observer must envelope his head and the ocular of the instrument with opaque cloth. *e*. Purkinje's phenomenon. In a light of moderate brightness, choose a bit of red paper and a bit of blue paper that are about equal in intensity and saturation, or better, make such a pair with the color-mixer by adding white or black till the intensity and saturation appear the same. Carry both into the full sunlight and notice which appears brightest. Carry both into a darkened room, or observe them in deep twilight, or through a very fine needle hole in a card, or even with nearly closed eyes, and again notice which seems brightest. Cf. also Ex. 142*a*.

Helmholtz: *Op. cit.*, G² 402-444; on *a*, 284-285, 322-324, 465, 466; on *b*, 469, 471-472; on *e*, 428-430, 443-444. G¹, 234, 280, 281, 317-321. F. 315, 369, 370, 420-425. Fick: *Op. cit.*, 200-202. Aubert, Phys. Opt., 531-536. Rood: *Op. cit.*, 181-194. For measurements of the just observable differences of intensity for different colors, see Helmholtz: *Op. cit.*, G² 402-416; Aubert, Phys. Opt., 531; Fick: *Op. cit.*, 177, and the references given by them. Benson: *Op. cit.*

132. Changes in saturation. Repeat Ex. 131*b*, using colored sectors or stars on white disks instead of black. If star disks are used, it is best to give the rays of the star a leaf shape, for the smaller quantities of color toward the outer ends of the narrow rays fail to

[1] Since the black of the disk is really a very dark gray, this is not an absolutelypure experiment, but is sufficiently exact for the purpose.

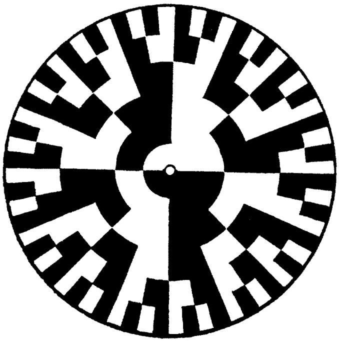
make an impression on the white. Notice the paling of the color when mixed with white and the relatively preponderating effect of the latter. Notice also a tendency to change in color tone as well as in saturation, especially when the amount of color is small. Red tends toward rose, orange toward red, indigo toward violet, blue-green toward blue, etc. According to Rood's experiments with the color-mixer, yellow-green and violet are unchanged; Helmholtz with spectral colors gets somewhat different results.

Helmholtz: *Op. cit.*, G² 322, 470-471, G¹ 281, F. 369. Aubert: Phys. Opt., 531-532. Rood: *Op. cit.*, 194-201.

133. Size of the colored field. The color sensation is not independent of the size of the retinal area stimulated, if the latter is small; and is also affected by the background against which the small colored area is seen. Paste on pieces of black and white cardboard small squares of several kinds of colored paper, one series 5 mm. square, one 2 mm. square and one 1 mm. square. Walk backward from them and notice their loss of color. Observe also the changes in color-tone.

Helmholtz: *Op. cit.*, G² 374-375, G¹ 300, F. 399-400. Aubert: Phys. Opt., 536-539. E. Fick: Notiz über Farbenempfindung, Pflüger's Archiv, XVII, 1878, 152 153.

134. Some Phenomena of Rotating Disks. Talbot-Plateau Law. In several experiments of this section use has been made of rotating disks in studying colors and color combination. All such use depends on the phenomenon of positive after-images (Cf. Ex. 116, *Amer. Jour. Psychol.*, IV, 1891-92, 486). A disturbance set up in the retina does not at once subside, but lasts an instant after the removal of the stimulus. If stimuli follow in sufficiently rapid succession the disturbances are added to one another and fused and the result is the same as though the stimuli had reached the retina simultaneously. The rate of succession necessary to give a uniform sensation is from 25 to 30 per second, the rate depending on the illumination of the disk, the higher rate being required for the greater illumination. When once this uniform sensation has been reached the color and brightness of any given concentric ring of the disk are the same that it would have if all the light reflected from it were evenly distributed over its surface, and no further increase in rapidity produces any effect upon its appearance. This is the Talbot-Plateau law. Rotate a disk like that shown in the cut, increasing the rapidity till the innermost portion gives a uniform gray. When this occurs, the rate of recurrence in the outer ring is 32 times more rapid than in the innermost, and yet no difference in shade is to be seen. To show that the gray is actually of the same brightness that would come from an even distribution of the light reflected from the whole surface of the ring, look at the disk when at rest through a double convex lens held at such a distance from the eye and disk that no distinct image is formed, but the disk looks an even blur of gray. When the disk is put in rapid rotation the gray remains unchanged.



On rotating disks and their phenomena in general cf. Helmholtz, *op. cit.*, G2 480-501, G1 337-355, F. 445-471. On the Talbot-Plateau law cf. Helmholtz, *op. cit.*, G2 482-483, G1 338-340, F. 446-450. Aubert, Phys. Opt., 515-516.

135. Some Phenomena of Rotating Disks. Brücke's experiment. As the disk used in the last experiment is allowed gradually to go slower and slower, there will be observed in one ring after another, beginning with the inner one, just as it loses its uniform character, a notable brightening. The white sectors now have opportunity to produce their full effect upon the retina before they are succeeded and their impression cut off by black sectors.

Helmholtz, *op. cit.*, G2 481-485, G1 338-341, F. 446-450. Aubert, Phys. Opt., 510.

136. Some Phenomena of Rotating Disks. The Münsterberg-Jastrow phenomenon. *a.* When the disk used in the last experiment gives a uniform gray, pass rapidly before it a thin wooden rod or thick wire, and notice that a multitude of shadowy images of the rod will appear on the disk. The number of images is greatest in the portion of the disk having the most frequent interchange of black and white. *b.* Exchange the disk for one carrying two or more colors. Notice the repetition of the phenomenon, and that the colors of the images are the colors (otherwise completely blended) which the disk actually carries. The explanation of the phenomenon is not altogether clear, but the sudden changes of the background against which the rod is seen seem to have an effect not unlike that of a stroboscopic disk or of intermittent illumination, which would show the rod at rest in its successive positions.

Jastrow: A Novel Optical Illusion. *Amer. Jour. Psych.*, IV, 1891-92, 201-208.

137. Some Phenomena of Rotating Disks. Fechner's colors. Rotate the disk used in Ex. 119 or that used in 134, or indeed almost any black and white disk with a less rapidity than that required to give a uniform gray, keeping the eyes from following the motion of the disk, and notice the play of colors on its surface. These vary with the rate of the disk and the intensity of the illumination. The colors may not at once appear, but are not difficult to get with steady and attentive gazing. The colors owe their existence to an analysis of the light of the white sectors, depending, not on the different wave lengths of the colors, as in the case of the prism, but on the differences in the times at which the different primary color sensations reach their maximum in sensation. The intermittent stimulation causes a rise and fall in the intensities of the fundamental sensations, but the instant of greatest excitation is not the same for all.

Helmholtz, *op. cit.*, G2 530-532, G1 380-381, F. 500-502. Aubert, Phys. Opt., 560.

138. Color-mixing. A general law of color-mixing, and one upon which almost all experiments with artificial colors must depend, may be stated as follows: Like appearing colors produce like appearing mixtures.[1] Thus an orange that is mixed from red and yellow spectral lights will produce the same purple when mixed with violet that spectral orange of like intensity would itself produce. The colored papers with which the experiments below are made are very far from simple colors (as can easily be seen by looking at scraps of them on a black background through a prism), yet they produce the same mixtures that spectral colors of equal tone, intensity and saturation would do. Three colors properly selected

1. This law of course has reference to the mixture of colored lights and not to mixtures of pigments upon the palette.

from the whole range serve to produce by their mixtures all the intermediate colors (though generally in less saturation) besides purple and white (*i. e.*, gray). The colors generally selected are red, green and violet. Green cannot be mixed from colors that themselves do not resemble it, *i. e.*, it can be mixed from yellow-green and blue-green, but not from yellow and blue, and not in anything like spectral saturation. *a.* Mix a yellow from red and green on the color-mixer. The yellow produced will be dark, and as a test of its purity should be matched with a mixture of yellow and black made with smaller disks set on above the first. In the same way mix a blue from green and violet that shall match a mixture of blue and black. *b.* From red and violet or blue, mix several shades of purple between violet and purple. *c.* From red, green and violet, mix a gray that shall match a mixture of black and white on the small disk.

For demonstrational purposes the result of mixing two colors in different proportions can be shown on a single disk of the star form (see Ex. 131) by painting the star in one color and the ground of the disk in another (or by pasting colored papers instead of painting), but in either case some trial will be necessary to determine the proper size for the rays.

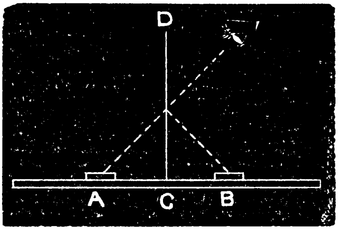
Helmholtz, *op. cit.*, G2 311-316, 320 322, 325-33, 350-357, 375 376, 473, 485, G1 272-277, 279-281, 282, 341, F. 359 365, 367-369, 450. Aubert, Phys. Opt., 521-524, 527-528.

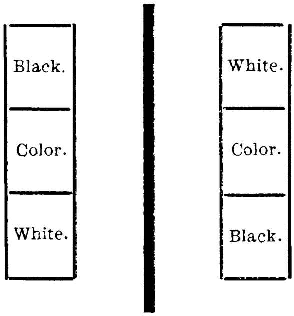
139. Complementary Colors. The combination of red, green and violet mentioned in the last experiment is not the only combination that will give white or gray. For every color there is another or complementary color, which mixed with it will give a colorless combination. Some of these pairs are red and blue-green, yellow and indigo blue, green and purple, blue and orange-yellow, violet and yellow-green. *a.* Try several of these pairs upon the color-mixer, matching the resultant gray carefully with a mixture of black and white on the small disk. It will probably be found in some cases that no possible proportions of the colored papers at hand will give a pure gray. In that case a little of the color complementary to that remaining in the gray must be added. Suppose the red and blue-green papers give, when combined, gray with a tinge of brown (*i.e.*, dark orange), a certain amount of blue or indigo must be added to compensate. For example, with certain papers 180° of blue-green +36° indigo +144° red make a gray that matches 90° white +270° black. To see the true complement of the red used it is then necessary to prepare a disk carrying green and indigo only in the proportions of 180 and 36, *i.e.*, 300° blue-green, 60° indigo. In the same way the complement of the blue-green used is a bluer red than that of the red paper, and may be seen by itself by mixing 288° red with 72° indigo. It is very important here, and in all cases where a resultant white or gray is to be observed, to have some undoubted white or gray in the field to prevent illusions over very faint tinges of color. *b.* Negative after-images when projected on a colorless gray or white surface are seen in colors complementary to those that give rise to the after-images. Compare a pair of complementary colors found in this way with the same pair as found on the color-mixer.

Helmholtz, *op. cit.*, G2 316-319, G1 277-278, F. 365-367. Aubert, Phys. Opt., 521-524.
Complementary colors can be well seen with polarized light. See picture of the schistoscope, an instrument for showing them by this means in Rood, *op. cit.*, 162; description of Rose's chromatometer (*Farbenmesser*), Helmholtz, *op. cit.*, F 397; also the Leukoskop, Helmholtz, *op. cit.*, G2 368, and references there given.

140. Other Methods of Mixing Colored Lights. *a.* The simplest of these methods is by reflection and transmission. The colors to

be mixed are placed on a horizontal surface on opposite sides of a vertical glass plate. The eye is brought into such a position that the reflected image of the colored field on the eye side appears to overlie the field on the other side seen through the glass. The glass must of course be of good quality and clean. The relative intensity of the colors can be varied by varying their distance from the glass. Bringing the colors near the glass or raising the eye, strengthens the reflected and weakens the transmitted light. Strips of paper placed with their ends next the glass will show an even blending from a mixture in which one predominates to one in which the other predominates, provided the illumination is equal. To mix two colors in exactly equal proportions, arrange them with black and white, as in the diagram below.





Glass.

Adjust the glass till the grays made by the black and white at the ends exactly match; the colors will then be mixed half and half.

By substituting a bit of glass on a black background for one of the colors and then placing the instrument so that a portion of clear sky may be reflected in the glass, it is possible to mix sky blue with its complement, or with any other color.

b. Colored areas placed side by side can be mixed with the aid of a double refracting prism. The prism doubles both fields and causes a partial overlapping. In the overlapped portion the colors are mixed.

c. Spectral colors can be mixed, though in an inexact way, without more apparatus than a prism and a piece of black cardboard. Fit a piece of black cardboard into the window frame so that it shall cover one pane completely. Cut in the middle of it two narrow slits (1-2 mm. wide and 10 cm. long), meeting each other at right angles and making a broad V. The cuts should be clean and sharp and the slits of uniform width. Look at this V from a distance, 10 or 12 feet, holding the prism vertical. Each arm of the V will give a spectrum, and where they cross, some spots of mixed color may be made out, especially the red and violet giving purple, and red and green giving yellow. The early studies of Helmholtz were

made with apparatus arranged on this principle, but more refined. If lines finer than can conveniently be cut in the cardboard are desired, they can easily be made (after a suggestion of Prof. Pickering) by tracing them on a piece of smoked glass. If the sunlight is allowed to fall on a prism and the spectrum is caught on a white wall or a screen, colors may be mixed with a double refracting prism like the colored fields mentioned above.

d. Something may be done in the way of mixing colored lights with a prism and narrow strips of paper or a diagram like Plate I, or still better, a similar diagram in which black takes the place of white, and *vice versa.* Since a prism refracts different kinds of light to different degrees, it produces a multitude of partially overlapping images of a bright object, which appear to the eye as colored fringes. (Observe through a prism a square inch of white paper on a black background.) These overlapping images may be illustrated by the following diagram, in which the horizontal lines stand for the images and the capital letters for the colors of light producing them.

```
                  a      b
V ———————————————————— V
   I ———————————————————— I
      B ———————————————————— B
         G ———————————————————— G
            Y ———————————————————— Y
               O ———————————————————— O
                  R ———————————————————— R
                  d      c
```

In the area *a b c d* all the images overlap and the white of the paper is still seen. Toward the left from *a*, however, the different kinds of light gradually fail, beginning with the red. The successive colors from greenish blue to violet result from the mixture of what remains. At the other end a similar falling away of the colors gives the succession from greenish yellow to red. In Fig. 1, Plate I, the spectra seen on the upper and lower edges of the square are brought side by side; on one side red, orange and yellow, and on the other greenish blue, blue and violet. The colors that stand side by side are complementary pairs both in color tone, intensity and saturation; for the greenish blue is the white of the paper less the red, and the blue the same less the red, orange and yellow, and so with the rest; and if the two spectra could be exactly superposed they would make precisely the white from which they originated.

If a very narrow strip of white upon a black ground is looked at through the prism, the images overlap less and another color appears, namely, green, as may be seen in Fig. 2 on the narrow white band between the black bars. When, on the other hand, a narrow black band on a white ground is taken, the spectra of the white surface above and that below partially overlap and give another set of mixtures. If the diagram is held near the prism at first and then gradually withdrawn from it, the advance and mixing of the spectra can easily be followed. Besides the greenish yellow at one end and the greenish blue at the other, there are a rich purple, complementary to the green beside it, and a white between the purple and the greenish yellow. The last is a white produced by the mixture of the blue of one spectrum with the complementary yellow of the other.

In Fig. 3 are shown a number of color mixtures with different proportions of the constituents. In the spectra from the white

PLATE I.

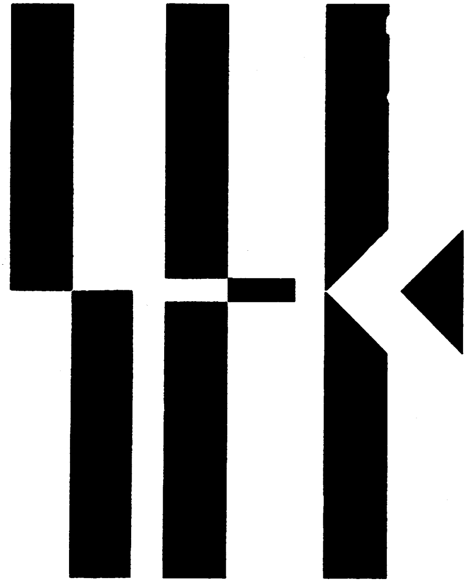


Fig. 1. Fig. 2 Fig. 3

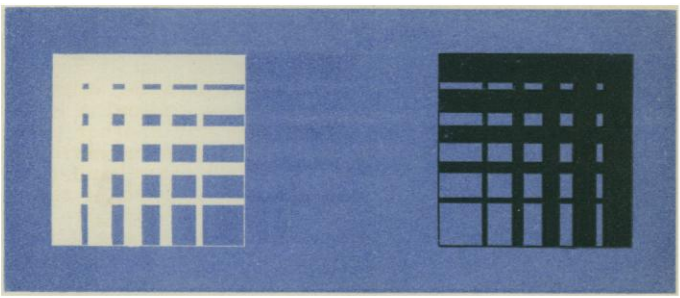


Fig. 4

triangle appear mixtures of each color in the spectrum seen on the white band in Fig. 2, with every other color found there. Upon the black triangle in the spectra from the white edges above and below are seen mixtures similar to those on the black band in the same figure. The diagram should be at such a distance from the prism that a little of the white and black triangles can yet be seen.

On methods of color mixing cf. Helmholtz, *op. cit.*, G2 350-357, 485, 491-493; G1 303-306, 341, 346-349; F. 402-407, 450, 457-461. Aubert, Phys. Opt., 521-524. Maxwell, *op. cit.*, On *a* and *d*, Benson, *op. cit.*

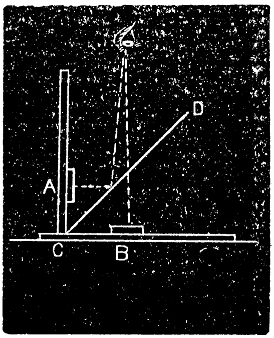
141. Contrast. The effect of one color on another, when not mixed with it, but presented to the eye successively or in adjacent fields, is known as contrast. Two kinds are distinguished, *Successive contrast* and *Simultaneous contrast.* The color that is changed or caused to appear upon a colorless surface, is known as the *induced color*; the color that causes the change is called the *inducing color.* Successive contrast is largely a matter of negative after-images, and their projection upon different backgrounds. Successive contrast: *a.* Prepare a set of colored fields of the principle colors, including white and black, say 3x5 inches in size, and some small bits of the same colors, say 1 cm. square. Lay a small square on the black field, get a strong negative after-image and project it first on the white and then on the other fields. Notice that the color of the after-image spot is that of the field on which it is projected minus the color that produced the spot; *e. g.*, the after-image of red projected on violet looks blue, and on orange looks yellow. Or, to say the same thing in other words, the color of the spot is a mixture of the color of the after-image with the color of the ground upon which it is projected. Thus the blue-green after-image from the red, when mixed with violet, gives blue; when mixed with orange gives yellow. Notice that when the image is projected upon a field of the same color it causes the spot on which it rests to look dull and faded, but when it is projected upon a field of complementary color, it makes the spot richer and more saturated. In general, colors that are complementary or nearly so are helped by contrast, those that resemble each other more nearly are injured in appearance. *b.* These effects in even greater brilliancy can be seen by laying the small square of color directly on the larger colored surface, staring at it a few seconds and then suddenly puffing it away with the breath. Cf. also Ex. 126. *c.* This contrast effect may be so strong as actually to overcome a moderately strong objective color. Place a small piece of opaque orange paper in the middle of a pane of red glass and look through the glass at a clear sky or bright cloud. The strength of the induced blue green will be sufficient to make the orange seem blue. *d.* The contrasting color may even be made to appear upon a surface faintly tinged with inducing color. Rotate one of the disks used in Ex. 132 or Ex. 131*b* rapidly enough to produce an even mixture. Bring the eye within six or eight inches of the disk, stare steadily at the centre for ten or twenty seconds; then suddenly draw back the head. The complementary color will appear to rush in upon the disk from all sides. The explanation is that after the withdrawal of the head the retinal image of the whole of the disk rests upon the part before fatigued by the intensely colored center of the disk.

Helmholtz, *op. cit.*, G2 537-542, G1 388-392, F. 510-515.

142. Mixed contrasts. When special precautions are not taken to exclude successive contrast, both kinds co-operate in the general effect. Some of the results are striking and beautiful. *a.* Colored

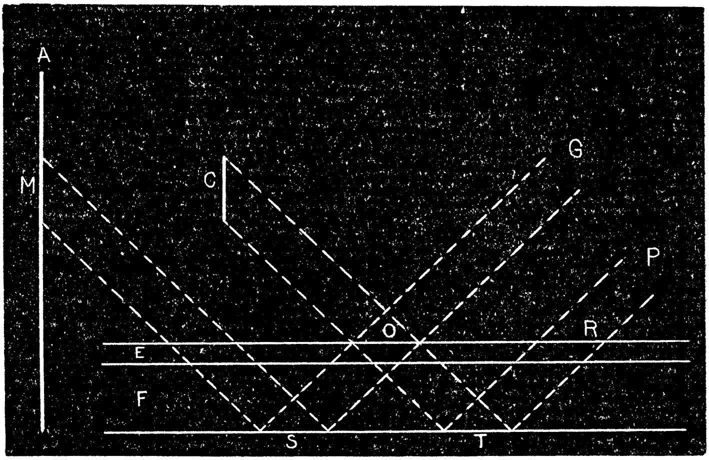
shadows. (1) Arrange two lights so that they shall cast a double shadow of a pencil or small rod upon a white surface, and regulate the brightness (or distance) of the lights so that the shadows shall be about equally dark. The daylight will answer for one light if it is not too strong, but it must come from an overcast sky, for the light from a blue sky is itself blue. Introduce different colored glasses one after another before one of the lights and notice the beautiful complementary color that immediately appears in the shadow belonging to that light. Cf. also Ex. 144. (2) Use a blue glass and adjust the relative intensities of the lights so that the yellow shadow appears at its brightest, and notice that it seems as bright as or brighter than the surrounding blue. As a matter of fact, however, it receives less light than the surrounding portions, for as a shadow it represents the portion of the field from which the light is partly cut off.

b. Mirror contrasts. (1) Ragona Scinà's experiment. Place upon the horizontal and vertical surfaces of the frame described above, white cards carrying black diagrams. Any black spot will answer, but for this experiment diagrams made up of sets of heavy concentric black rings (lines a quarter of an inch wide), separated by white rings of triple width, give an excellent effect. The diameters should be so chosen that a black ring on the horizontal diagram shall correspond to a white one on the vertical and *vice versa*, and shall appear to lie in the midst of the white when the diagrams are combined in the way immediately to be described. A pair of diagrams made up of parallel black bars, a quarter of an inch wide, separated by quarter inch spaces, and so placed in the instrument that they give a checker-board pattern when combined, are useful for keeping in the field a true black with which the changed colors can be compared. The diagrams being in place, hold between the two at an angle of 45° a pane of colored glass, say green, and observe that the black of the horizontal diagram seems tinged with the complementary color, that is, purple. This contrast color may often be improved by slightly altering the inclination of the glass, or by changing the relative illumination of the diagrams by interposing a colorless screen between one or the other of them and the source of light, or by shifting the whole instrument. The mechanism of this experiment will be readily understood after a consideration of the accompanying cut. The glass plate is represented by *C D*, the black portion of the vertical diagram by the projection opposite *A*, that of the horizontal diagram by the projection at *B*. The light reaching the eye from the white portion of the horizontal diagram is colored green by the glass; that from the white portion of the vertical diagram is reflected from the upper surface of the plate, and is therefore uncolored[1]. The mixture of the two gives a light green field. For simplicity, we may assume that no light comes from the black portions of the diagram. In the portion of the light green field corresponding to the black of the vertical diagram, the white component will be wanting and the green will appear undiluted; in the portion cor-



[1] A small portion is also reflected from the lower surface of the glass, so contributes a small amount of green.

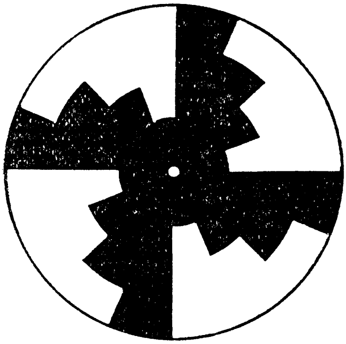
responding to the black of the horizontal diagram, the green component will be wanting and the faint white (*i. e.*, gray) should appear by itself. It does not, however, because of the contrast color induced upon it. As a matter of fact, the black portions are not absolutely black; the small amount of light that comes from them tends on one hand to make the green one (image of the black of the vertical diagram) a little whiter, and on the other hand to counteract the contrast in the purple one by adding to it a little green. Try the experiment with other glasses than green. (2) Another form of the mirror contrast experiment is as follows. Place a mirror where the sky or a white surface of some kind will be seen reflected in it. Lay upon its surface a plate of colored glass, green for example, and hold a little way above it a narrow strip of black cardboard or a pencil. Two images will be seen: one a vivid green, the other a complementary purple. The green image belongs to the surface reflection of the colored glass, as may be proved by observing that when the strip of cardboard touches the surface, the green image touches it also. The explanation will readily be understood from the accompanying diagram.

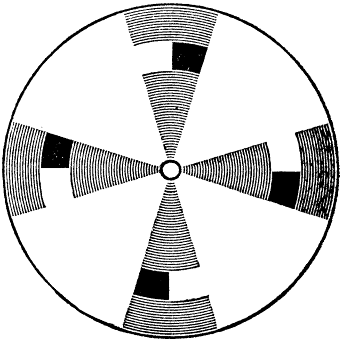


In the diagram, *A* represents a white surface, *C* the strip of cardboard, *E* the plate of green glass, *F* the glass of the mirror. As in Ragona Scinà's experiment, the white surface is reflected unchanged from the upper surface of the green glass. A good deal of the light, however, traverses the green glass and the mirror, is reflected from the back of the mirror, traverses the green glass again, and finally, as a strong green, mixes with the white reflected from the surface of the green glass, forming, as in Ragona Scinà's experiment, a light green field. The black strip *C* is reflected at *O*, that is to say, at *O* is a place where the white from the surface *A* is cut off, and only green from *M*, by way of *S*, is present, hence its image appears green. But *C* is also reflected at *T* (or its light is wanting there), so that the white reflected from *R* is unmixed with green. By contrast, it appears purple. It is easy, by substituting for *C* a gray strip that will send some light through the glass at *O* and *R*, to show that contrast can suppress an actually present objective color.

c. Meyer's experiment. Lay on a large colored field a small piece of gray or even black paper (*e. g.*, 1 cm. wide by 2 cm. long), and cover the whole with a piece of semi-transparent white paper. The contrast color will appear on the gray paper. If thin tissue paper is used, more than one thickness may be needed for the best result. R. Jung, Heidelberg, sells a book (for Becker's *Florversuche*) of alternate leaves of colored and tissue paper, with two gray rings attached, made expressly for Meyer's experiment. Paper mats, woven one way of gray paper and the other of colored, show this contrast beautifully, as Hering mentions. They may easily be made from kindergarten materials.

d. Mixed contrasts with the color-mixer. (1) Disks made on the pattern of the cut at the left show beautiful contrasting grays.





The same can be shown also by laying a number of small sheets of tissue paper over one another in such a way that they partially overlap, making a portion where there is but a single thickness, and next it a portion where there are two thicknesses, and next that again one of three thicknesses, and so on. When the whole is held up to the light, the contrasts of adjacent portions are very easily seen. (2) Contrast colors can be shown finely with disks like that in the cut at the right, in which the shaded portions represent color, the black portions black and the white, white. A little care is necessary in fixing the proportions of the color to white and black in the disks for contrast colors, but in general the brightness of the gray should be about that of the color.

On *a* cf. Helmholtz, *op. cit.* F. 517-519, 531; G.[1] 393-395, 405; G.[2] 551-553. Hering: Ueber die Theorie des simultanen Contrastes von Helmholtz; Die farbigen Schatten, Pflüger's Archiv, XL, 172. V. Bezold, *op. cit.*

On *b* (1) cf. Helmholtz, *op. cit.* F. 531-532; G.[1] 405-406; G.[2] 557-558. Hering: Ueber die Theorie des simultanen Contrastes von Helmholtz; Der Spiegelcontrastversuch. Pflüger's Archiv, XLI, 1887, 358-367. Wundt, *op. cit.*, I, 482. See also the physiologies in general.

On *b* (2) cf. Dove: Versuche über subjective Complementarfarben, Pogg. Ann., XLV, 1838, 158. Helmholtz, *op. cit* F. 532, G.[1] 406; G.[2] 558. V. Bezold, *op. cit.*

On *c.* Helmholtz, *op. cit.* F. 523, 530-531; G[1] 398, 404 405; G.[2] 547-548. Hering: Ueber die Theorie des simultanen Contrastes von Helmholtz; Der Contrastversuch von H. Meyer und die Versuche am Farbenkreisel, Pflüger's Archiv, XLI, 1887, 1-29.

On *d.* Helmholtz, *op. cit.* F. 538-543; G.[1] 411-414, G.[2] 544-547. Hering, *op. cit.* on *c.* V. Bezold, *op. cit.* Meyer, Pogg. Ann., XCV, 170, Phil. Mag., Ser. 4, IX, 547.

For quantitative measurements of contrast of grays cf. Ebbinghaus, Die Gesetzmässigkeit des Helligkeitscontrastes, Sitzber. d. k. Preus. Akad., Berlin, Sitz. v. 1, Dec., 1887. Lehmann: Ueber die Anwendung der Methode der mittleren Abstufungen auf den Lichtsinn; Die quantitative Bestimmung des Lichtcontrastes. Wundt's Philos. Studien, III, 1886, 516-528.

143. Conditions that influence contrast. *a*. Contrast effects are stronger when the colors are near together. (1) Lay a bit of white paper on a black surface, *e. g.*, a piece of black velvet, and notice that the paper is whiter and the velvet blacker near the margin of the paper than elsewhere, notwithstanding that the eye moves about freely. This has received the name of "Marginal contrast" (*Randcontrast*). (2) On a piece of gray paper, the size of a letter-sheet, lay two strips of colored paper close side by side (*e. g.*, pieces of red and yellow or of green and blue, 1 cm. wide by 4 cm. long). Below them to the right and left as far apart as the paper will permit, lay two other strips of the same size and color, red on the red side of the former pair, yellow on the yellow side. Notice the effect of the difference in distance on the contrasting pairs. Contrast of this sort is at a maximum when one color entirely surrounds the other.

b. Effect of size. When the area of the inducing color is large and that of the induced color is small, the contrast is shown chiefly on the latter; when the two areas are of about equal size, as in *a* (2) above, the effect is mutual. Try with large and small bits of paper upon a colored field.

c. Borders and lines of demarkation that separate the contrasting areas tend to lessen the effect by excluding marginal contrast. Repeat Ex. 142*c*, using two slips of gray paper 5 mm. wide by 2 cm. long, substituting a piece of moderately transparent letter paper for the tissue paper. When the contrast color has been noted, trace the outline of one of the slips with a fine ink line upon the paper that covers it. Notice that the color nearly or quite vanishes. This experiment and others like it play an important part in the psychological, as opposed to the physiological, explanation of simultaneous contrast (see Helmholtz, *op. cit.* F. 533 f., G.[1] 406 f., G.[2] 559 f., but cf. also Ex. 144). Such a black border will, however, also make a weak objective color invisible. A disk like that in the cut accompanying Ex. 142*d*, when provided with a second contrast ring, marked off on both its edges with a firm black line, shows a weakening of the induced color in the bordered ring.

d. Saturation. Contrast effects are generally most striking with little saturated colors. (1) Compare the effect of increasing, decreasing and extinguishing the second non-colored light in the colored shadow experiments. It is necessary, however, to see to it that reflected light from the walls and surrounding objects does not complicate the experiment. (2) Compare the intensity of the contrasts in Meyer's experiment (Ex. 142*c*) before and after the application of the tissue paper. Notice also the part played by the white light mixed with the colored light in the mirror contrast experiments above. Powerful contrasts with the most saturated colors can be observed, however, when the proper conditions are fulfilled.

On helpful conditions in general cf. Helmholtz, *op. cit.* F. 513-514, G.[1] 390-391, G.[2] 540-541.
On *c*. Helmholtz, *op. cit.* F. 539-542, G.[1] 411-414, G.[2] 546-547.
On *d*. Helmholtz, *op. cit.* F. 528-524, G.[1] 399-400.

144. Simultaneous contrast. The effects of simultaneous contrast are often lost in the more striking ones of successive contrasts, and the first requisite of an experiment on simultaneous contrast is the exclusion of the successive. This is not difficult in experiments in colored shadows. *a*. Place a piece of white paper in such a position that it may be illuminated at once from the window (if the day be overcast) and from a gas-jet. Set upon it a small block or other object, about 1½ by 3 inches in size, and either black or white

in color. Light the gas and observe the two shadows, one cast by the light from the window, the other by the gas. The first will appear yellowish, the second clearly blue.[1] Adjust the distance and position with reference to the light so that the shadows shall appear about equally dark, and the blue shadow shall be as sharply bounded as possible, and to that end have the shadow cast by the edge rather than the flat side of the flame. The color of the yellowish shadow is objective and due to the yellow of the gas-flame, that of the blue is due to the contrast, but largely as yet to successive contrast. Put a dot in the centre of the blue shadow, to serve as a fixation-point, and another on the edge. Fasten a paper tube (preferably blackened inside) so that it can easily be shifted from one dot to the other. Cut off the gas-light by holding a card between it and the block; adjust the tube so that the dot in the middle of the shadow may be fixated without any of the parts of the field outside of the shadow being seen. Wait until all of the blue has disappeared from the shadow, and then, still looking through the tube, remove the card. The field remains entirely unchanged and appears, as before, a colorless gray. The former blue color is thus shown to be subjective and due to contrast with the yellow lighted area in which it lies. *b.* Cut off the gas-light again and adjust the tube so that the dot in the edge of the shadow may be fixated. Taking great precaution not to move the eye, withdraw the card. The part of the field of the tube filled by the shadow will appear bluish, that of the remainder reddish-yellow. After a little time of steady fixation, cut off the gas-light once more and observe the instant reversal of the colors. The shadow now appears in reddish-yellow, the rest of the field blue. The color of the shadow, both before and after the final interposition of the card, is due to simultaneous contrast, in the first case with the reddish-yellow light, and in the second with its after-image.

Helmholtz explains all cases of simultaneous contrast as errors of judgment; in the case of the colored shadow, for example, we mistake the yellow of the gas-lighted field for white and consequently find the shadow which is really gray to be bluish. In the case of this particular experiment, Hering and Delabarre seem to have shown this psychological explanation unnecessary and a physiological one all sufficient, and Hering has done the same for other forms of experiments.

Cf. on simultaneous contrast in general. Helmholtz, *op. cit.* F. 515-547, G.[1] 392-418, G.[2] 542 ff. Hering, *op. cit.*, under Ex. 142. On colored shadows, cf. Helmholtz, *op. cit.* F. 517-519, G.[1] 394-396, G.[2] 551-553.

On Helmholtz's theory, cf. Helmholtz, *op. cit.* F. 533-538, G.[1] 392, 407-411, G.[2] 543 ff. Hering, *op. cit.* under Ex. 142 ; also, Ueber die Theorie des simultanen Contrastes von Helmholtz : Die subjective " Trennung des Lichtes in zwei complementäre Portionen."

Delabarre : Colored Shadows, AMERICAN JOURNAL OF PSYCHOLOGY, II, 1888-89, pp. 636-643

For quantitative measurements of simultaneous contrast, see Kirschmann: Ueber die quantitativen Verhältnisse des simultanen Helligkeits und Farben-Contrastes, Wundt's Philos. Stud., VI, 1890.

145. Simultaneous contrast. Hering's binocular method. *a.* Use the binocular color-mixer described above in the note on apparatus. Set a red glass in the right frame, a blue glass in the left. Look fixedly through the colored glasses of the instrument at the cork ball below, bringing the eyes close to the glasses and the

---

[1] This setting of the experiment succeeds best when the daylight is weak, as, for example, just before the lights are usually lighted in the evening. If the experiment is to be made in broad day, the light must be reduced by curtains or otherwise ; if at night, there must be two lights, one corresponding to the window and one to the gas, and the latter must shine through a pane of colored glass. If yellow glass is used the colors will be the same as those in this experiment.

nose between them. Adjust the side screens till the white ground below appears in a uniform light violet from the binocular mixture of the red and blue (cf. Ex. 153). The narrow strip of black paper on the white is seen double, the right hand image bluish, the left yellowish. *b*. The possibility of successive contrast is, however, not yet excluded. That may be accomplished as follows: Lay a sheet of black paper over the whole of the white field and its black strip; rest the eyes; and finally, when everything is in readiness, and the eyes again fixed on the ball, swiftly draw away the black paper. The contrast colors are seen on the instant, before any motions that might introduce successive contrast have been made.

Hering argues that this experiment is conclusive against the psychological explanation of simultaneous contrast, unless a separate unconscious judgment is to be made for each eye, for that which consciously appears is a light violet field, and the contrast color to that should be a greenish-yellow, and both images of the strip should be alike, whereas, as a matter of fact, the images appear in different colors, neither of which is the color required.

Hering: Beitrag zur Lehre vom Simultankontrast, Zeitsch. f. Psychol. I, 1890, 18-28. For a different experiment supporting the same conclusion, see Hering's paper.

146. Influence of judgment in visual perception. While in the previous experiment a psychological explanation seems sufficient for the facts, psychical action is not excluded, even by Hering, from a considerable share in sense perception. In the following experiments judgment coöperates in the result. *a*. Place upon the color-mixer a short-pointed star of white cardboard, or even a square, when in sufficiently rapid rotation, it appears as a white central circle surrounded by a more or less transparent ring. While it is in rotation bring behind it a broad strip of black cardboard of somewhat greater length than the diameter of the star from point to point. As the edge of the card advances it can be seen not only behind the transparent ring, but, apparently, also behind the opaque central circle, and the portions of the latter in front of the black card seem darkened by its presence. The illusion holds, though with a lightening instead of a darkening effect when a white card is moved behind a black star. The illusion fails by degrees if the card is kept motionless, but may be observed to a certain extent when the star is at rest. *b*. Cover a piece of black cardboard smoothly with tissue paper and notice that it seems, at first, blacker than it afterwards proves to be on comparison with other grays. *c*. In mixing colors by reflection (Ex. 140*a*), notice the tendency to see one color through the other instead of seeing the mixture of the two. This tendency may be so strong at first as to interfere, to a certain extent, with the success of the experiment. Cf. also Ex. 152.

On the difficulty of judging small differences in the color of surface that present other small unlikenesses. cf. Hering, *op. cit.* under Ex. 142*c*.
On *a*., Sanford, *Science*, XXI, 1893, 92.

147. An effect exactly the reverse of contrast appears when a figure in black or white is placed upon a colored ground. The black figure appears to darken the ground and the white to brighten it. This is a method often used in polychromatic decoration. Observe the effect on the blue ground in Fig. 4, Plate I. It may be observed occasionally in plaid fabrics, and is shown very satisfactorily in kindergarten mats woven in checker-board pattern of colored and gray papers. If a set of grays is used so that the strips may range from a black at one side to a white at the other, the corresponding shading of the colored paper is striking.

V. Bezold, *op. cit.* 182-183, and Plate V.

Binocular Phenomena of Light and Color.[1]

148. In general the two eyes coöperate to bring about a single visual result, but the union of the impressions upon the two retinæ is influenced by a number of circumstances. *a.* If the stimulus to one eye is considerably stronger than that to the other, the sensation in the latter is in most cases totally suppressed. Close one eye and look at a sheet of white paper with the other, letting the open eye move about freely. There is no tendency for the darkened field of the closed eye to assert itself. *b.* When, however, the effect of the stimulus in the open eye is somewhat weakened by steady fixation, such a tendency is to be observed, and the whole of the field of the open eye, except a small area about the point fixated, may be, from time to time, suppressed by the dark field of the closed eye. A slight motion will, however, instantly restore the first. Cf. also Ex. 118. *c.* A field that contains sharply marked objects or contours will generally triumph over one that does not. Try combining the letters below in such a way that the B's are superposed. In these the white field of either eye which corresponds to A or C in the other eye will generally not triumph over the letters.

A B   B C

On the Binocular Phenomena of Light and Color in general, see Fechner: Ueber einige Verhältnisse des Binocularen Sehens, Abhandlungen der kgl. sächs. Ges der Wiss. VII. 1860, pp. 339-564. Helmholtz, *op. cit.* F. 964-999, G.[1] 767-796. Hering: Hermann's Handbuch der Physiol., III, Th. i, 380 385, 576-577, 591-601 ; Beiträge zur Physiologie, 308-316. Aubert: Grundzüge der physiologischen Optik, 499-503, 550-554. Wundt: Physiol. Psychol. 3te. Aufl. II., 177-179, 183-189. Ebbinghaus: Ueber Nachbilder im binocularen Sehen und die binocularen Farbenerscheinungen überhaupt, Pflüger's Archiv, XLVI, 1890, 498-508. Titchener, Ueber binoculare Wirkungen monocularer Reize, Wundt's Philos. Studien, VIII, 1892, 231-310. Chauveau: Several articles in the Comptes rendus, CXIII, 1891, 358, 394, 439, 442.

149. Fechner's paradoxical experiment. Hold close before one eye a dark glass, such as is used in protecting the eyes, or a piece of ordinary glass moderately smoked over, or even a black card with a good sized pin-hole in it, allowing the other eye to remain free. It is easy to see that the binocular field is darkened by the interposition of the dark glass. If, however, the eye behind the glass is closed, or the light wholly cut off from it by holding a black card in front of the glass, the field appears decidedly brighter, that is to say, cutting off a portion of the stimulus received by the total visual apparatus, has caused an increased intensity of sensation. The experiment fails for very dark and very light glasses. Several explanations have been given, but that of Aubert, according to which the sensations of the two retinæ blend in a sort of average result when the difference is not too great, but one wholly suppresses the other when it is very great, seems to be the most satisfactory, and with this Hering also in the main agrees.

150. Rivalry. When the two retinæ are stimulated separately with strong light of different colors, or are confronted with otherwise incongruous fields, *i. e.*, fields that cannot be given a unitary

---

[1] The experiments that follow can all be made with the stereoscope, but practice will enable the experimenter to combine the diagrams with free eyes, either by crossing the lines of sight (fixating a point nearer than the diagram), or by making them parallel or nearly so (fixating a point beyond the diagram). This skill the experimenter should try to acquire. In these experiments it is important that the eyes should be of approximately equal power, and if the poorer eye cannot be helped with lenses, the vision of the other must be somewhat reduced by the interposition of a sufficient number of plates of ordinary glass.

interpretation, there result a peculiar instability and irregular alternation of the colors over part or the whole of the combined fields of vision. This apparent struggling of the fields is known as *Retinal rivalry.* Hold close before one eye a piece of blue glass, before the other a piece of red glass, and look toward the sky or a brightly lighted uniform wall. The struggle of colors will at once begin. The same may be observed with a stereoscope when the usual paired photographs are replaced by colored fields, or even with no apparatus at all, when both eyes are closed and turned toward a bright sky and one of them covered with the hand. Rivalry has been explained as due to fluctuations of attention, and some observers find that it can be more or less controlled by attention (Helmholtz); Fechner discusses the attention theory, and finds it insufficient. Hering and others regard the changes as of a purely physiological origin. Cf. Ex. 151*b*.

151. Prevalence and rivalry of contours. By "contours" is here meant lines of separation where fields of one color border upon fields of another color. *a*. Combine stereoscopically the two bars below, and notice that it is the contours that suppress the solid parts of both the black and white. This figure gives excellent results when colors are substituted for the black and white.

Notice a similar triumph of the contours of the cross over the lines, and of the lines over the central black of the cross in Fig. XI, or an enlargement of it.

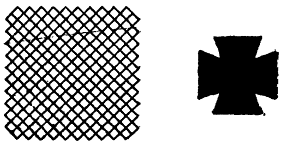


Fig. XI

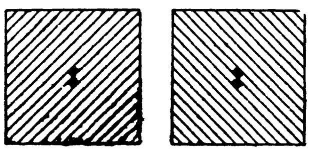
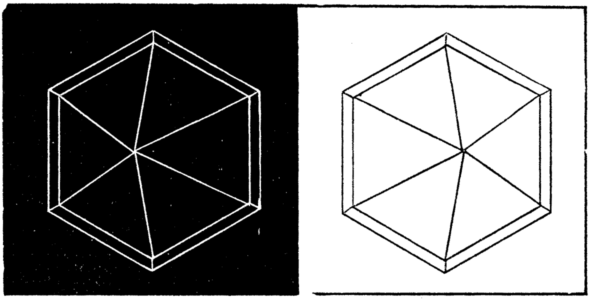


Fig. XII

b. Notice the rivalry of the contours in all of these figures. *c*. Such diagrams as Figs. XI and XII are suitable for the study of the part played by attention in rivalry. While it is doubtful that mere attention to one field or the other will cause it to predominate, it yet seems possible by indirect means to cause it to do so. If attention is given to an examination of the lines and small squares in Fig. XI, or if one of the series of lines in Fig. XII is counted, they will appear to be somewhat assisted in their struggle with the cross or the other set of lines. *d*. A printed page has a decided advan-

tage. Try a diagram in which a printed page is brought into competition with a field of heavy cross lines. The lines will be found to yield to the print, at least, at the point at which the reader is looking. Two printed pages, however, become hopelessly mixed, and it is hard to say how much of the advantage, when a single one is used, is due to its superior power as a holder of attention, and how much to its excellence as a set of contours. A portion of the power of contours is probably to be explained by the mutual intensification of both the black and the white by contrast, but a part is perhaps due to a strong tendency, observable in other cases also, for the eyes (and attention) to follow lines, and especially outlines.

152. Luster. When one of the rival fields is white and the other colored (especially when one is white and the other is black), there results, besides the rivalry, a curious illusion of shine or polish, known as *Binocular lustre*. *a*. Examine in the stereoscope a diagram made like the accompanying cut, and notice the graphite-like shine of the pyramid. The explanation seems to be that polished sur-



faces, which at some angles reflect light enough to look white, and at others appear in their true color, have often in previous experience given rise to such differences of sensation in the two eyes, from which in this instance we infer a polish on the object seen in the diagram. *b*. A species of monocular lustre (or transparence) is to be observed when black or white or colors are combined by means of the reflection color-mixer, especially when the inclination of the plate is so changed that one color appears to be reflected in the surface of the other, or to be seen through and behind it. The experiment works well when real objects are reflected in the surface of the glass, the reflecting power of the latter appearing as if transferred to the horizontal surface on the opposite side.

153. Binocular color-mixing. The result of simultaneous presentation of different colors to the two eyes is not always rivalry or lustre. If the colors are not too bright and saturated and the fields are without fleck or spot to give one the predominance, a veritable though somewhat unsteady mixture of the colors may result. *a*. Place a red and a blue glass of equal thickness in the binocular color-mixer, and adjust the side screens till the proper amount of white light is mixed in with that transmitted from below. The mixture will be seen on the white field below. Try also with other combinations of glasses. The mixtures obtained in this way are not exactly the same in appearance as the monocular mixtures studied above. *b*. The same effect may be conveniently obtained with a stereoscope, from which the middle partition has been removed.

Try with equal areas of dull colors of little saturation. Hering recommends two squares of red and two of blue, set at equal distances in a horizontal line, the two reds on one side, the two blues on the other. When the middle pair are combined stereoscopically, they show a mixed color, while the unmixed colors can be seen for comparison beside them. He also suggests the use of lenses to prevent sharp focusing of the eyes upon the contours, which interfere with the mixture. Complementary colors are said to be more difficult to fuse than those standing nearer in the color scale. Cf. also Ex. 149. For diagrams that bring in binocular perspective to aid in mixing the colors and for a specially adapted stereoscope, see Chauveau.[1]

154. Binocular contrast. The side-window experiment. Stand so that the light from the window falls sidewise into one eye, but not at all into the other. Place in a convenient position for observation a strip of white paper on a black surface. The paper when looked at with both eyes appears perfectly colorless. On looking now at a point nearer than the bit of paper (*e. g.*, at the finger held up before the face), double images of the bit will be seen. The two images will be different in brightness and slightly tinged with complementary colors. The image belonging to the eye next the window (which may be recognized by its disappearance when that eye is closed) will appear tinged with a faint blue or blue-green color, the other with a very faint red or yellow. The light that enters the eye through the sclerotic is tinged reddish-yellow, and makes the eye less responsive to that color; the white of the paper strip therefore appears bluish. It appears darker partly for a similar reason, and perhaps also, as Fechner suggests, because it lies in a field which for the eye in question is generally bright. The reddish color of the other eye's image of the strip is explained as due to contrast with the first, but whether this contrast is a purely psychical matter, or whether it is to be explained by the action of the stimulus in the first eye upon the second, as there seems some reason to think, is as yet uncertain. Its greater brightness is probably due to the fresher condition of the eye to which it belongs, and to contrast with its less brilliant field. The same thing is often to be noticed when reading with the lamp at one side, or even when one eye has been kept closed for a short time while the other has been kept open. The double images are in nowise essential; simple alternate winking will show decided differences in the condition of the two eyes.

155. Binocular after-images. Lay a bit of orange-colored paper on a dark ground, and provide two white cards. Hold one of the cards close to the left eye, but a little to one side, so as *not* to hide the bit of paper. Hold the other eight or ten inches from the right eye in such a way as to hide the paper. Look at the paper for a few seconds with the left eye, then bring the card before it. A faint, washy, orange-colored positive after-image will appear on the card before the right eye. This after-image is supposed to belong to the right eye's half of the visual apparatus, possibly to the central, *i. e.*, cerebral, part.

---

[1] Comptes rendus, CXIII, 1891, p. 442.